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ADAPTIVE SIGNAL PROCESSING FOR
IONOSPHERIC DISTORTION CORRECTION

D. J. Belknap
R. D. Haggarty
B. D. Perry

MARCH 1970

Prepared for

DIRECTORATE OF PLANNING AND TECHNOLOGY
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

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FOREWORD

This report covers work accomplished for an Over-the-Horizon Backscatter Radar Project (7160) by The MITRE Corporation, Bedford, Mass., under Contract No. AF 19(628)-5165. The contract sponsor was the Electronic Systems Division of the Air Force Systems Command.

REVIEW AND APPROVAL

This technical report has been reviewed and is approved.

JOSEPH N. ALLRED, Captain, USAF
Staff, Development Engineering Division
Directorate of Planning and Technology

ABSTRACT

Ionospheric distortions limit the usable signal bandwidth of HF over-the-horizon paths. By measuring the transfer function of the path and correcting for it in real time improved bandwidth capability results. To determine the feasibility of such a real-time correction technique, data has been gathered on an HF link operated by Stanford University and analyzed by computer at MITRE. A non-real time computer simulation of a correction technique has shown that for the bandwidths analyzed, the correction technique is feasible and that the corrections will not deteriorate significantly for several seconds.

ACKNOWLEDGMENT

The ionospheric sounding data presented here was collected over a link built and operated by Stanford University. Their participation and help in this experiment is greatly appreciated.

The assistance of others at MITRE, especially Don Bungard and Leo Hart of the technical staff and Jane Markey, is also acknowledged.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF ILLUSTRATIONS	vi
SECTION I INTRODUCTION	1
SECTION II THEORETICAL ADAPTIVE PROCESSING TECHNIQUES	3
SECTION III IONOSPHERIC TRANSFER FUNCTION MEASUREMENT TECHNIQUE	5
SECTION IV ADAPTIVE PROCESSOR REALIZATION	7
SECTION V MITRE-SEL EXPERIMENT AND DATA ANALYSIS	9
SECTION VI SUMMARY	31

LIST OF ILLUSTRATIONS

<u>Figure Number</u>	<u>Page</u>
1 SEL/MITRE Oblique Sounding Experiment	10
2a Amplitude vs. Frequency	11
2b Phase versus Frequency	11
2c Phase Residuals versus Frequency	11
3 Weighted Transform of First Sweep	13
4 Transform of Ideal Signal with 40 db Taylor Weighting	15
5 Corrected Transforms for Sweeps 2 through 7	16
6 Amplitude and Phase Residuals vs. Frequency for First Sweep	17
7 Weighted Transform of First Sweep	19
8 Corrected Transforms for 10 Seconds of Data	20
9 Upper Record: Amplitude (A_1) and Phase (ϕ_1) versus Frequency over 900 KHz band Lower Record: Transform of Upper Record	21
10 Corrected Transforms over 18 Seconds	22
11 Upper Trace: Amplitude (A_1) and Phase (ϕ_1) versus Frequency over 900 KHz Band at the MUF Lower Trace: Transform of Upper Trace	24
12 Corrected Transforms up to 12 Seconds Later	25
13 Amplitude (A) and Phase (ϕ) versus Frequency over a 3 MHz Band	26
14 Distortion Correction over a 3 MHz Band Upper Record: Uncorrected Fourier Transform Lower Record: Corrected Fourier Transform 5 Seconds Later	27
15 n^{th} Sweep Corrected by $(n - 1)^{\text{th}}$ Sweep	29
16 Transform of A_1 and Third Order Curve Fit on ϕ_1	30

SECTION I

INTRODUCTION

Transmission of HF signals via ionospheric refraction is limited by ionospheric distortions. These distortions appear as dispersion, absorption fading, multiple ray paths and faraday rotation, all of which vary with time. Compensation for distortion would permit the use of increased bandwidth, thereby effecting multipath isolation and improving resolution, accuracy and clutter rejection. The aim of MITRE adaptive processing techniques program has been to measure the characteristics of this medium, devise techniques that are capable of correcting for the distortions, and build equipment which tracks or adapts to changes in the ionospheric characteristic in real time.

Early in the program a theoretical adaptive processing technique was devised. Simultaneously it was established that suitable ionospheric data, to which the adaptive processing technique could be applied, was not available but that an ionospheric sounder capable of producing the required data was operational between Lubbock, Texas and the Stanford Electronics Laboratory (SEL) of Stanford University. This sounder was ideally suited because of its slowly sweeping, phase coherent, linear FM waveform. Since MITRE possessed digital recording equipment and a library of digital signal processing programs, a cooperative experimental venture between MITRE and Stanford was entered into. Data gathering exercises were performed in February and June of 1967.

This paper presents distortion measurements made over this one-hop oblique path and the results of a computer simulation of a correction technique as applied to these data.

SECTION II

THEORETICAL ADAPTIVE PROCESSING TECHNIQUES

If the ionosphere is modeled as a linear time invariant filter (time invariant over the time required for measurement and correction), its characteristic can be represented by a transfer function

$$I(f) = E(f) e^{jD(f)} \quad (1)$$

where $E(f)$ is an arbitrary amplitude characteristic as a function of frequency and $D(f)$ is an arbitrary phase characteristic as a function of frequency.

The inverse to the ionospheric transfer function, if it is realizable, can be represented as the reciprocal of the amplitude characteristic and the complex conjugate of the phase characteristic, as shown in Equation 2.

$$I_{\text{inverse}}(f) = \frac{1}{E(f)} e^{-jD(f)} \quad (2)$$

This inverse function is the basis for the corrections described in this paper. A receiver processor capable of assuming this inverse transfer function would be able to correct for all undesired signal distortions. The mismatch, subsequent degradation in signal-to-noise ratio and parameter distortion associated with any inverse filter in the presence of multipath would not be acceptable for all applications.

In these instances compensation for dispersion, but not multipath, can be accomplished by applying a correction derived from a smoothed fit to the phase characteristic. (This technique has the advantage of approximating matched filter conditions.)

SECTION III

IONOSPHERIC TRANSFER FUNCTION MEASUREMENT TECHNIQUE

The ionospheric transfer function could be obtained from the ionospheric impulse response. However, it is difficult to contain enough energy in a narrow impulse. Or the ionospheric transfer function could be obtained from the amplitude and phase of CW frequencies spaced across the frequency band of interest. The CW frequencies, however, must all be phase and amplitude calibrated.

The technique of this experiment is made possible because of the development by Hewlett Packard and Stanford Electronics Laboratory of a phase coherent frequency synthesizer.¹ This synthesizer can be programmed to step at a very fast rate from one frequency to the next in small frequency steps and in a phase coherent manner. An excellent approximation to a linear frequency modulation is thereby generated. This linear FM signal is transmitted through the ionosphere and upon reception is demodulated by mixing it with a delayed replica of the transmitted waveform. Normally, such a correlation process yields a constant frequency directly related to the time delay from transmitter to receiver. However, due to ionospheric distortion the output signal contains amplitude and phase modulation. In fact, due to the linear time-frequency relation of the sounding signal, the amplitude and phase

¹HF Measurement Using Extended Chirp-Radar Techniques, by R. B. Fenwick and G. H. Barry. Stanford Electronics Laboratory, Technical Report No. 103, June 1965.

modulation which emerges from the correlation mixer, as a function of time, is the amplitude and phase transfer function (Equation 1) of the ionosphere. Thus, a direct measure of the ionospheric transfer function can be obtained by taking quadrature samples of the output waveform at equal time intervals. This is true, because for large time-bandwidth product linear FM waveforms the amplitude is nearly constant and the phase is nearly quadratic as a function of either time or frequency. When the ionospheric distortions are included in the path, it is only necessary that the phase and amplitude distortions be slowly varying with respect to the phase variation of the modulating waveform.

There are three major advantages of the linear FM waveform. Phase calibration is automatic once the linear FM waveform has been achieved. Energy is transmitted continuously providing high energy per sample, and narrow band signals present in the HF band are discriminated against.

SECTION IV

ADAPTIVE PROCESSOR REALIZATION

The manner in which the above described measurement can be applied to correct or compensate for distortion depends heavily upon the modulation that is being transmitted and received. For example, to have a real-time processor capable of receiving arbitrary waveforms requires the implementation and control of an adaptive filter whose transfer function is the inverse of the ionospheric path. In this general case, a tapped delay line with amplitude and phase weights on each tap could be continuously controlled to provide the inverse transfer function. Or, a bank of band-pass filters with amplitude and phase weights on each filter could be employed.

Although linear FM is an ideal waveform to sound the ionosphere, it would not be necessary to use this waveform for subsequent transmissions if the generalized inverse filter were implemented. However, if the signal transmitted consists of a frequency vs time function and if the receiver consists of a correlation mixer, a programmed oscillator, and a spectrum analyzer, then a more easily implemented alternative to the generalized inverse filter can be employed. In such an instance, the phase correction can be made by modifying the receiver local oscillator, and the amplitude correction can be made by a time-varying gain control in the receiver channel. Since the initial goal of the MITRE program is to demonstrate the feasibility of ionospheric distortion correction, the technique of active control of receiver gain and phase

is employed. Linear FM is used both for measuring the ionospheric path and for subsequent transmissions to be corrected. The received data is recorded and the correction is applied in a computer in non-real time.

SECTION V

MITRE-SEL EXPERIMENT AND DATA ANALYSIS

Figure 1 shows a block diagram representation of the joint MITRE-SEL experiment. The Texas transmitter, the ionosphere, and the Stanford demodulator are shown. The processing and recording equipment built by MITRE is shown within the dotted lines. The IF signal is mixed in quadrature mixers to approximately DC. After low pass filtering, these signals are sampled, converted to digital form and stored on magnetic tape. Separating the signal into quadrature sine and cosine components allows both amplitude and phase to be sampled at a single point in time. Once the data is in digital form, further equipment distortions are avoided and manipulations of any type can be performed in a digital computer.

The particular implementation employed a digital stepping recorder whose normal data storage rate limited the bandwidth of the received IF signal to 50 Hz. The signal frequency band of interest was positioned within the recorder bandwidth by selecting an appropriate local oscillator frequency. The signal recorded was usually received one-hop via the F layer.

Data were recorded over a period of several hours on February 25, 1967. During this session nine frequency regions, each 350 kHz wide were swept repetitively for twelve seconds. Of the 34 records analyzed two examples are included here. The sweep rate was 1 MHz/second. Figure 2 shows the received signal for the first of a set of sweeps

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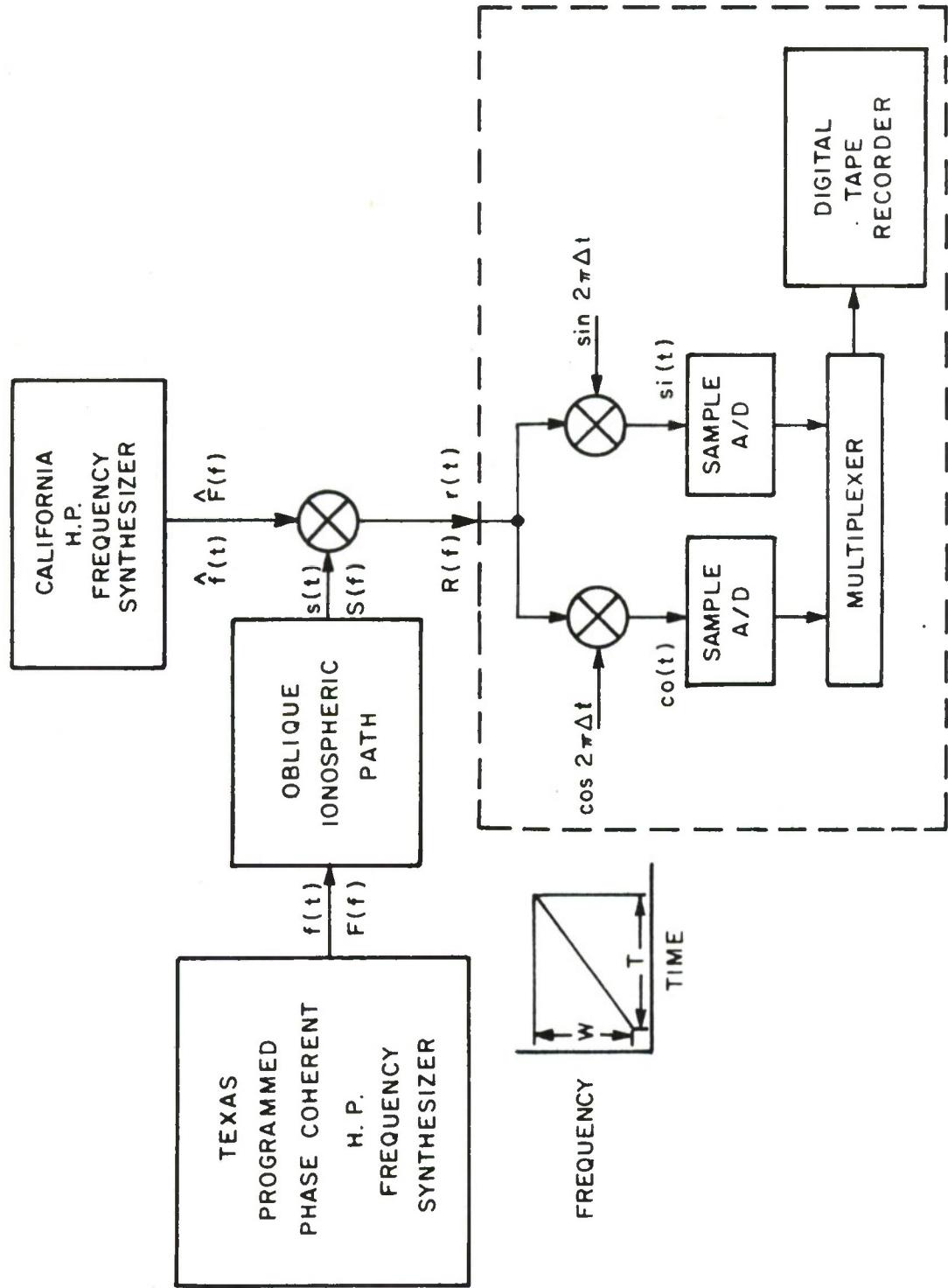
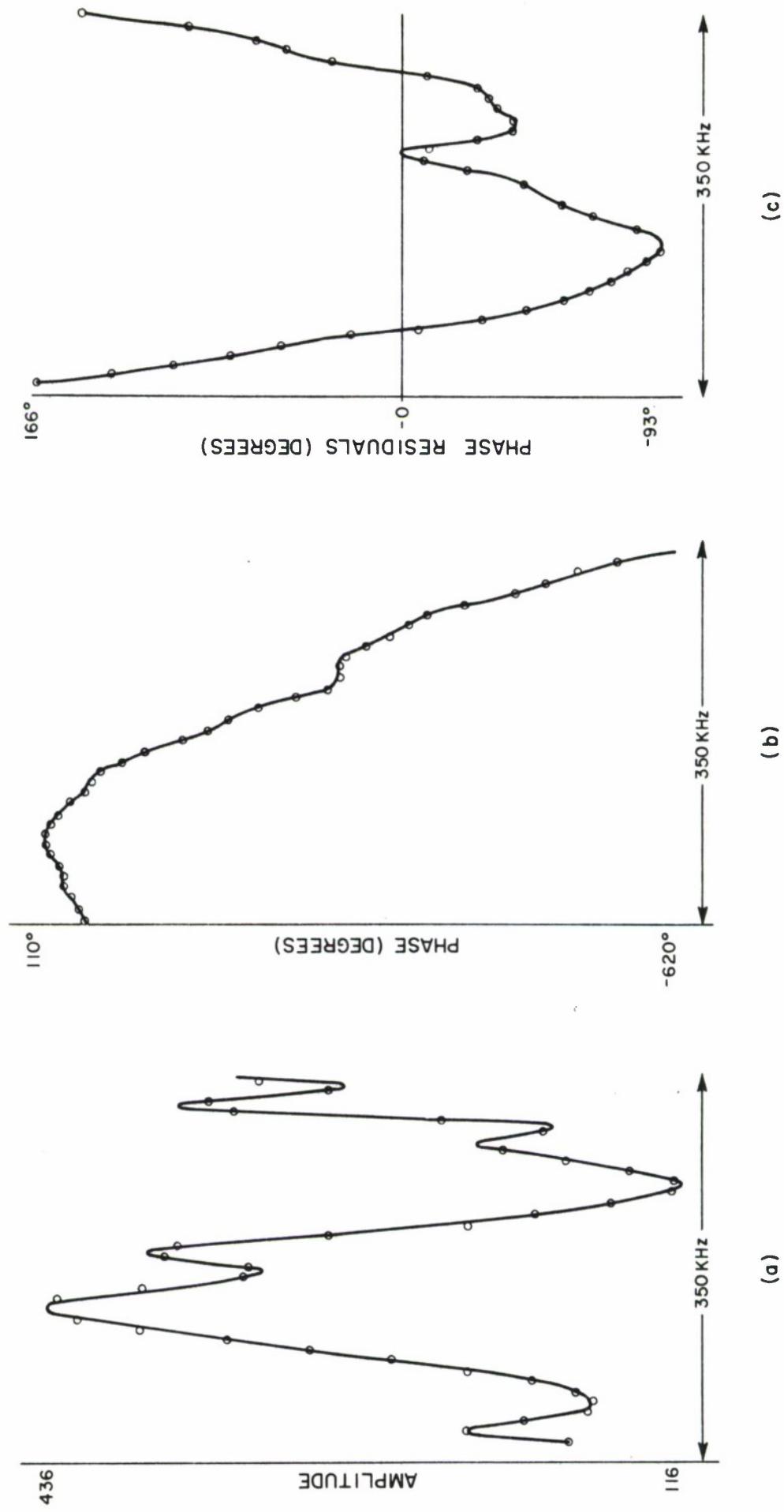


Figure I. SEL/MITRE OBLIQUE SOUNDING EXPERIMENT

Figure 2. AMPLITUDE, PHASE AND PHASE RESIDUALS vs FREQUENCY



between 20.15 MHz and 20.5 MHz. The maximum usable frequency (MUF) was approximately 26 MHz at this time. Figure 2a shows amplitude and Figure 2b shows phase versus frequency for the same sweep, while Figure 2c shows the phase residuals after a best straight line (second-order polynomial) fit. The amplitude and phase residuals shown are a measurement of the ionospheric transfer function. The amplitude recording shows a fluctuation of about six cycles in the band swept as well as a lower perturbation rate of about 1.3 cycles. The maximum and minimum amplitude values differ by about 4 to 1. The phase residuals curve roughly approximates a parabola with a maximum phase excursion of 259 degrees. A perfectly parabolic phase residual would imply a perfectly linear delay dispersion. For this assumption, the delay dispersion can be computed from the phase distortion knowing the linear FM slope of 1 MHz per second. The dispersion and the maximum phase excursion ϕ_{\max} are related as follows:

$$\text{dispersion} = \frac{8 \phi_{\max}}{360 \text{ (bandwidth)}} \quad (3)$$

where bandwidth is 350 kHz in this case, and ϕ is in degrees.

Solving Equation (3) for this example, the dispersion is equivalent to 16.5 μ sec of delay. The Fourier transform corresponds to a time domain impulse response. Figure 3 shows the transform of this sweep. A 40 db Taylor weighting was used to suppress sidelobes. The 16.5 μ sec of dispersion calculated assuming a perfectly parabolic

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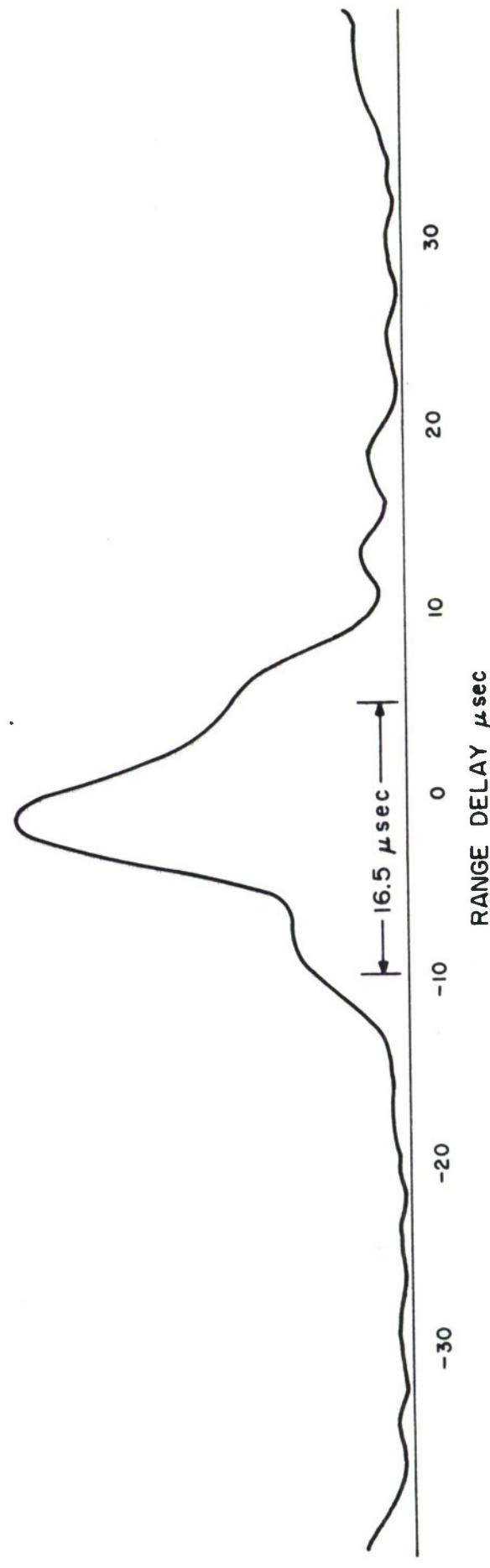


Figure 3. WEIGHTED TRANSFORM OF FIRST SWEEP

phase error corresponds quite closely to the broad base of the main lobe of the transform. For comparison purposes the weighted transform of an ideal rectangular amplitude and linear phase signal is shown in Figure 4. The time delay (range) resolution of this function is 4 μ sec.

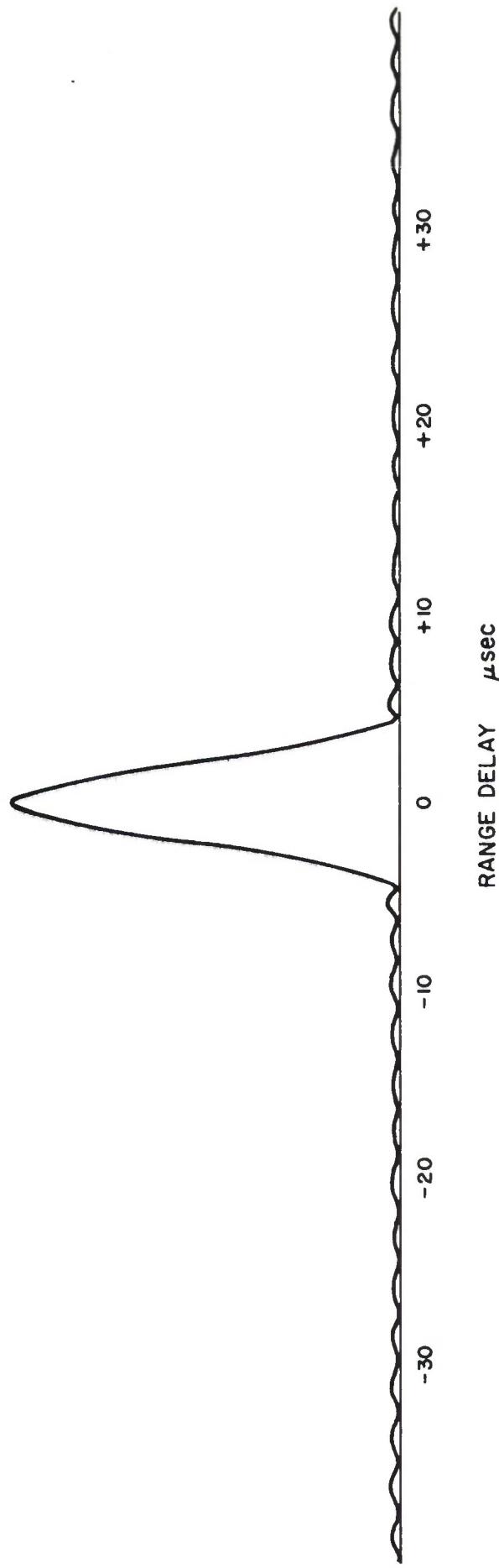
Amplitude and phase residuals for subsequent sweeps are then computed. With the first sweep acting as a reference, subsequent sweeps are compared to it by taking the ratio of the amplitudes and the difference in the phase angles. The weighted Fourier transform is then computed:

$$\mathcal{F} \left[\left(\frac{A_n}{A_1} \right)_{\text{wtd}} \angle \phi_n - \phi_1 \right] \quad (4)$$

If the ionosphere had not changed its character during the interval between the first and n^{th} sweeps, the two sets of data would be identical and the transform would be identical to that of Figure 4. For the data being discussed, Equation (4) is plotted for the six subsequent sweeps. These results, shown in Figure 5 one above another, are nearly ideal.

The second example of a 350 kHz sweep is one wherein the swept region was just below the MUF where the dispersion is quite severe and non-linear. The amplitude fluctuation in Figure 6a changes frequency across the swept region. This results in a smearing of the secondary lobe after transforming. Note also how the amplitude decreases as the

Figure 4. TRANSFORM OF IDEAL SIGNAL WITH 40 db TAYLOR WEIGHTING



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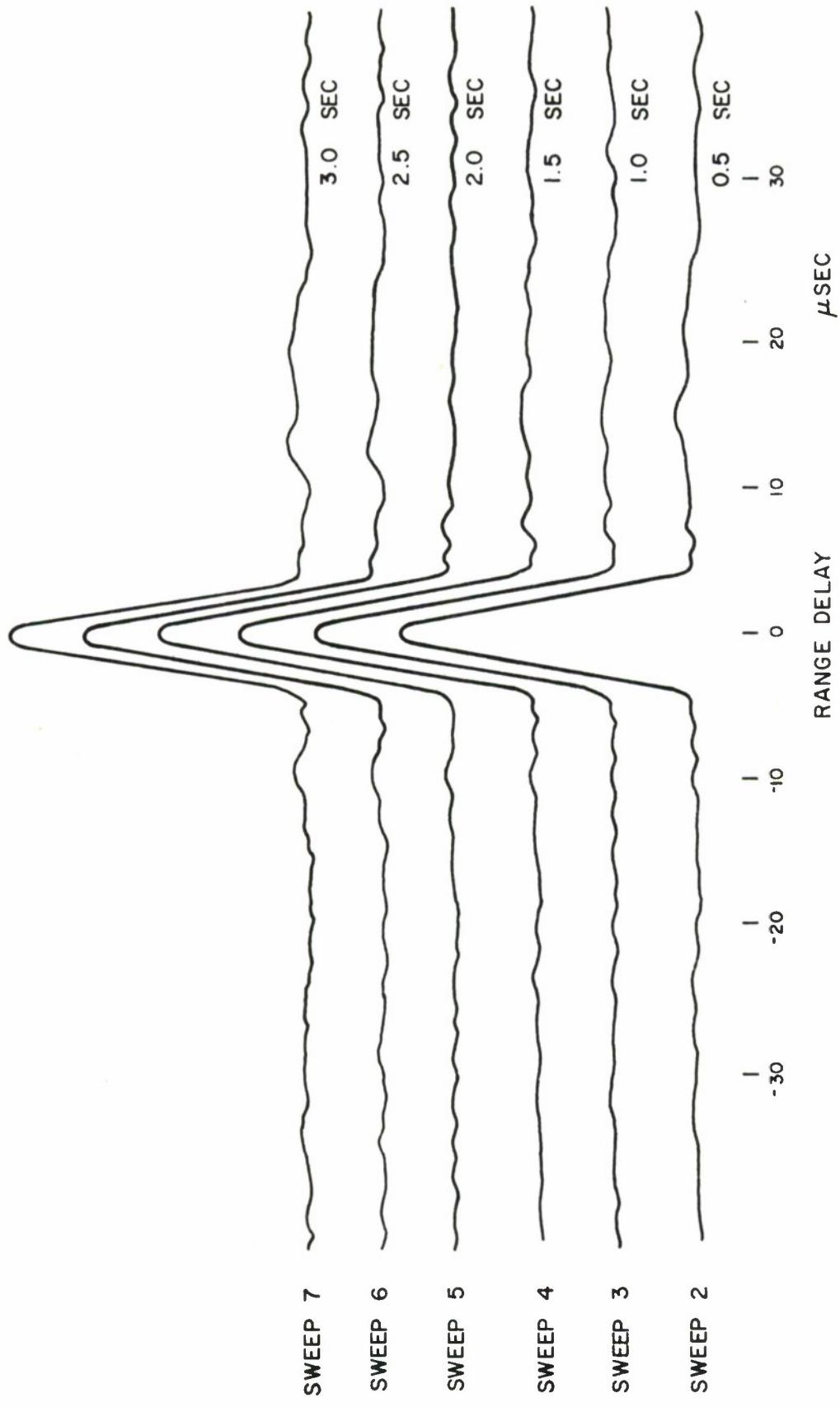


Figure 5. CORRECTED TRANSFORMS FOR SWEEPS 2 THROUGH 7

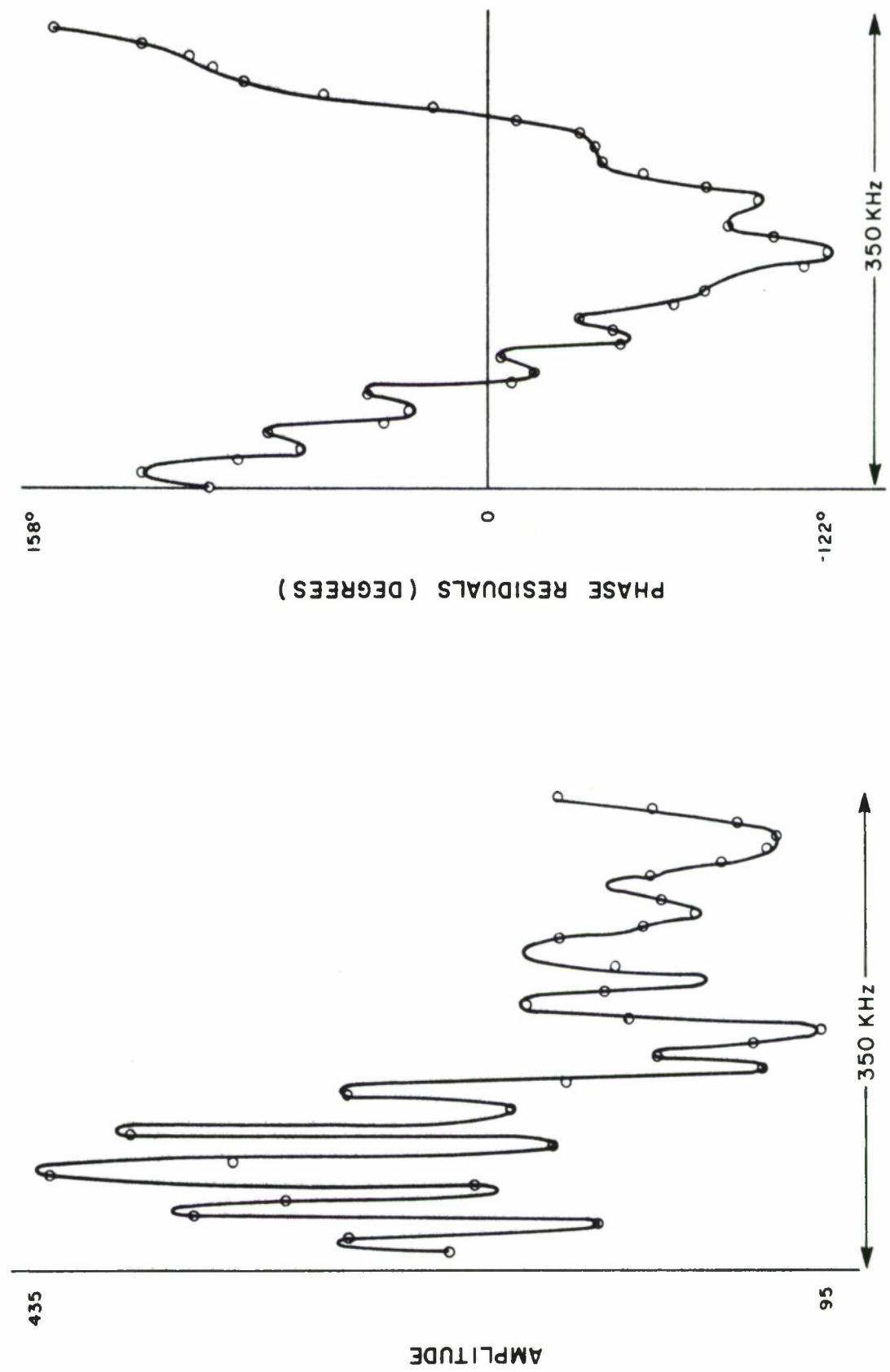


Figure 6. AMPLITUDE & PHASE RESIDUALS

IA-22,442

MUF is approached. The phase residuals to a first order fit (Figure 6b) exhibit the same variable rate fast fluctuation as the amplitude data, as would be expected from a secondary lobe. In addition, the more-or-less triangular shape of the plot indicates that the delay dispersion is not linear. The weighted transform of the second sweep is shown in Figure 7. The smeared secondary signal and broad main lobe are particularly evident. The transforms of Equation (4), which simulate the corrected signals, are shown in Figure 8. Even after 10.5 seconds the main lobe is considerably improved while the secondary signal has not been affected very much by the correction process. The sweeps missing were discarded due to equipment malfunctions.

Additional data were recorded at Stanford, California on June 20, 1967 over a twenty-four hour period. These data fall into two categories: 900 kHz and 3 MHz frequency sweeps. In each case a particular frequency region is swept repeatedly for 20 seconds. Of a total of 52 cases of 900 kHz data two examples are now discussed.

The first example is of data taken about 9 PM local time between 10.5 and 11.4 MHz. Amplitude (A_1) and phase residuals to a best straight line fit (ϕ_1) and their weighted transform are shown in Figure 9 for the first sweep. The corrected weighted transforms shown in Figure 10 extend for 18 seconds after the original sweep. In this case, nearly ideal results are obtained for five or six seconds and quite acceptable results for the full 18 seconds.

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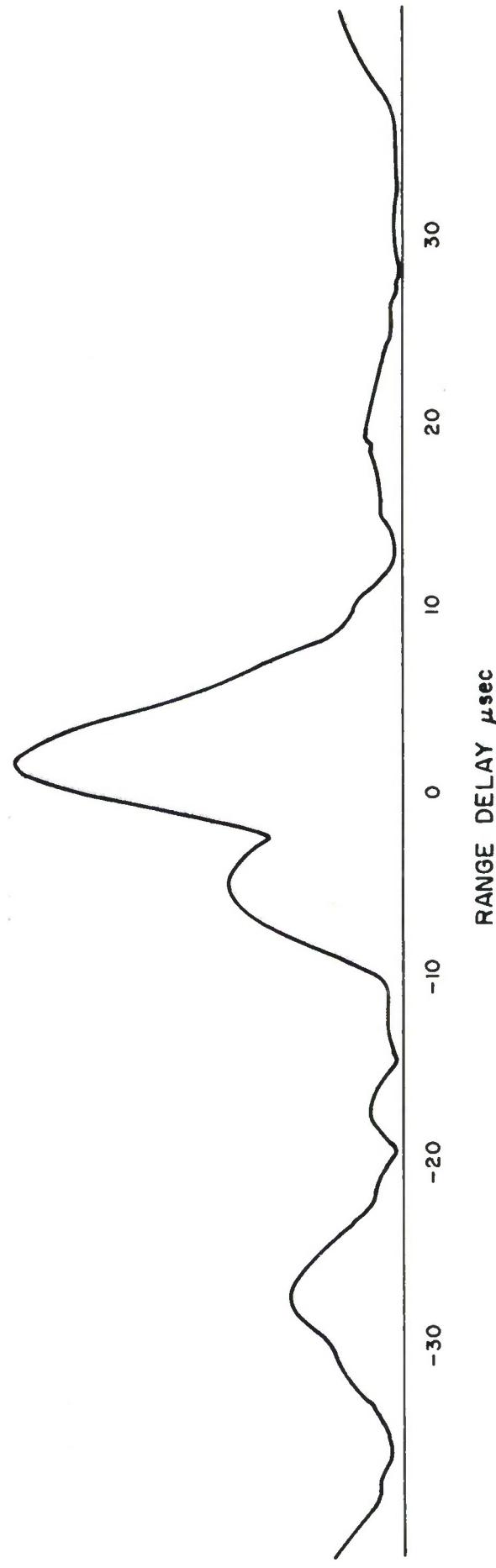
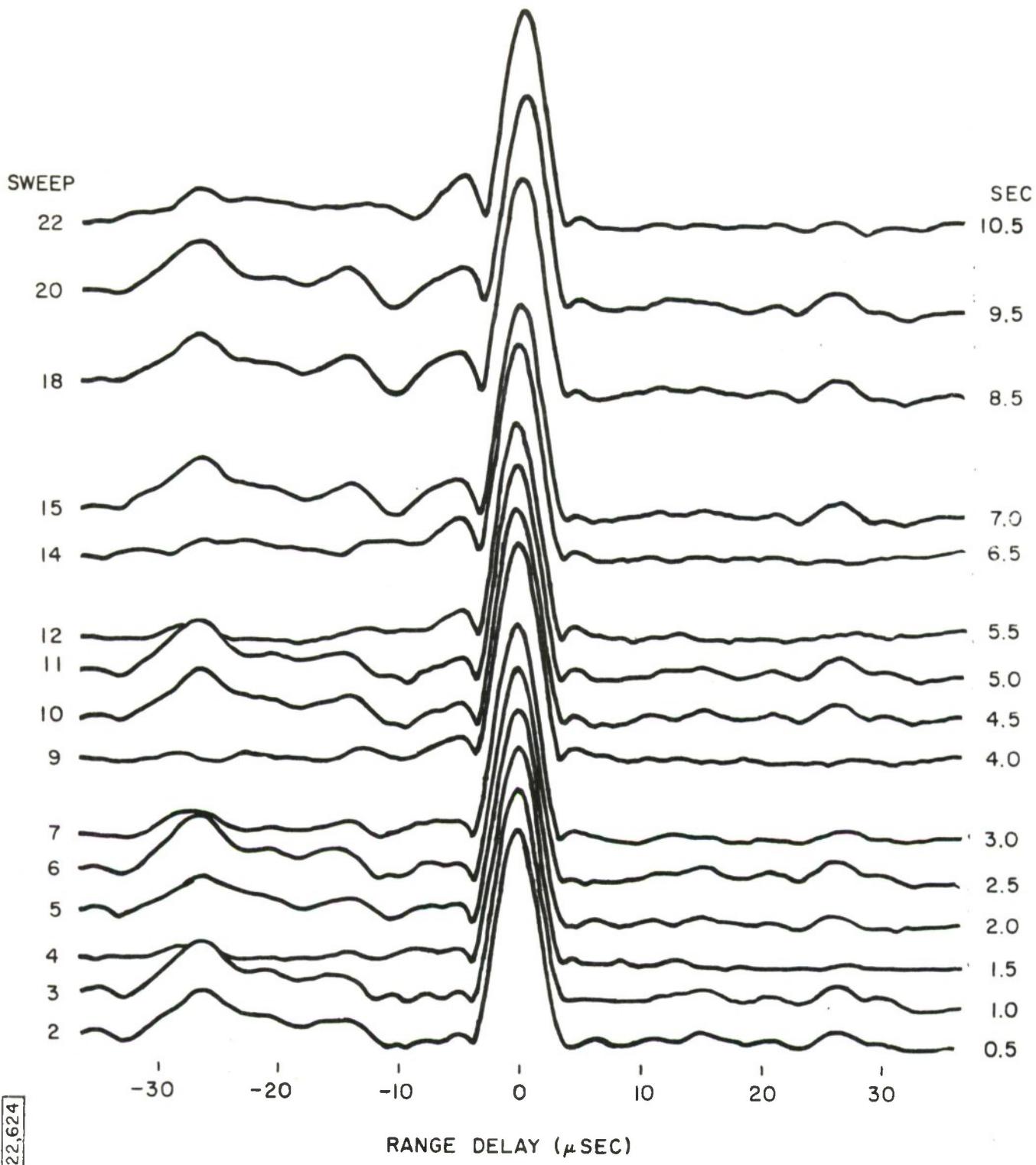


Figure 7. WEIGHTED TRANSFORM OF FIRST SWEEP



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Figure 8. CORRECTED TRANSFORMS FOR 10 SECONDS OF DATA

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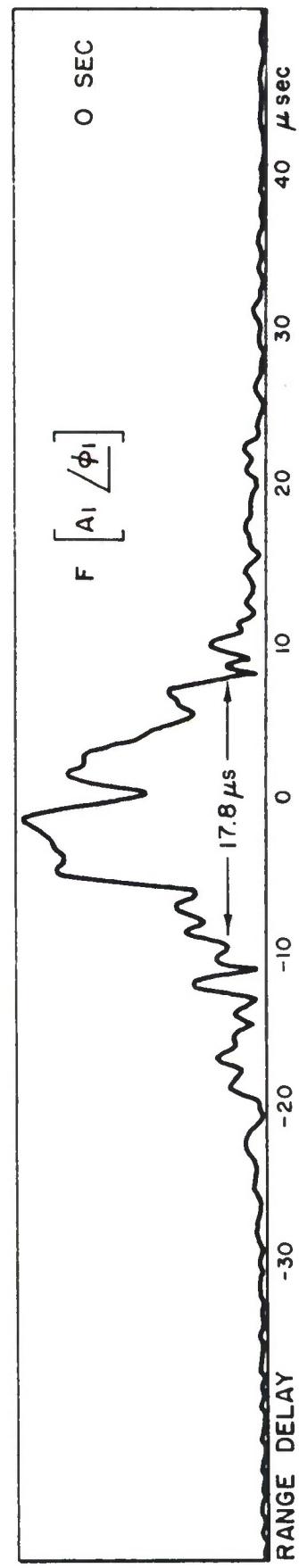
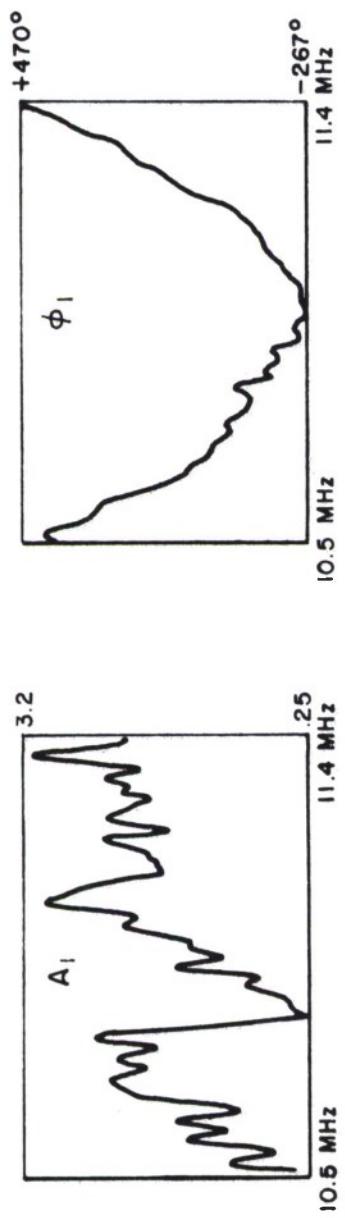


Figure 9

UPPER RECORD: AMPLITUDE (A_1) AND PHASE (ϕ_1) VERSUS FREQUENCY OVER 900 KHz BAND
LOWER RECORD: TRANSFORM OF UPPER RECORD

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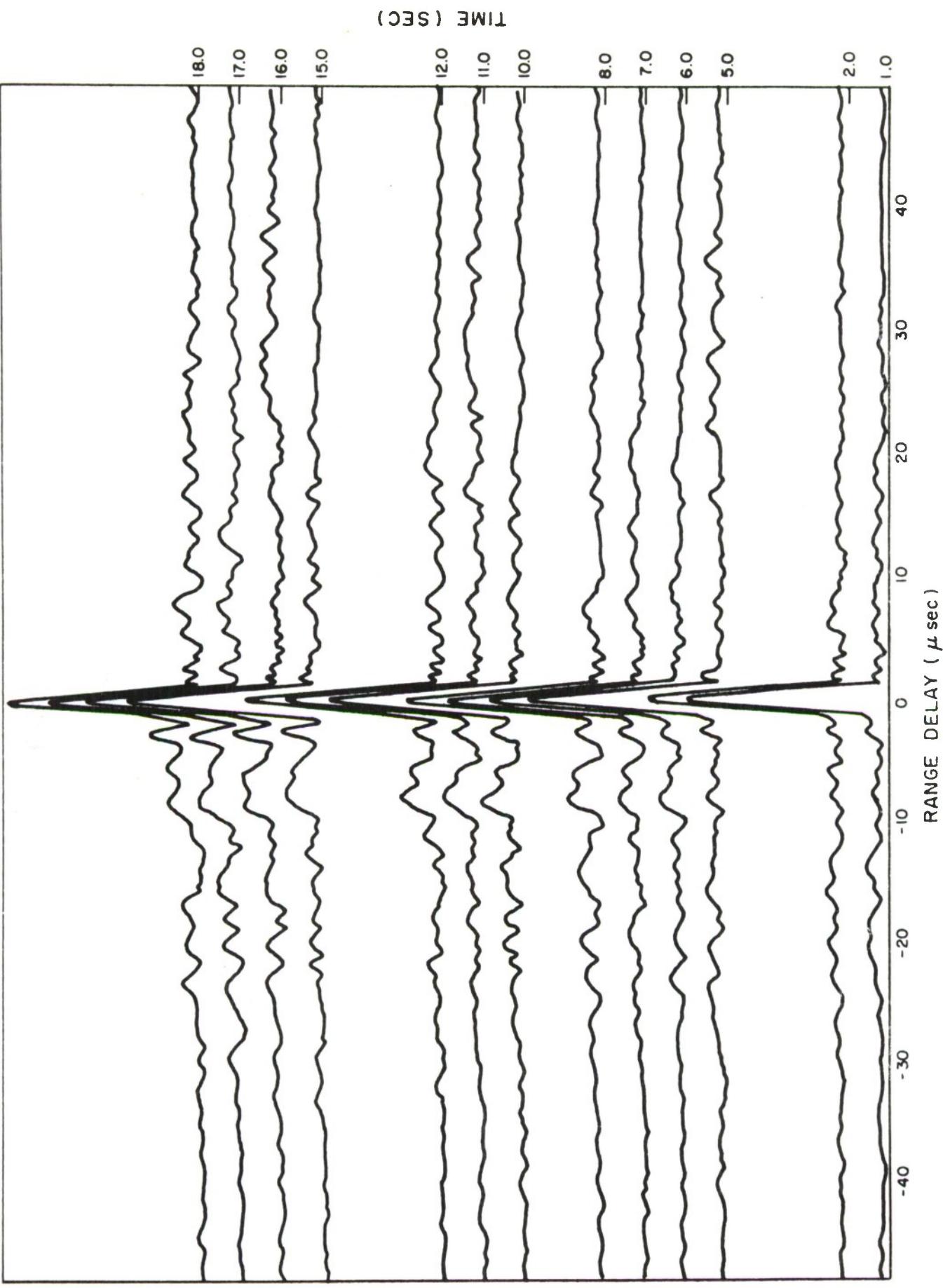


Figure 10 CORRECTED TRANSFORMS OVER 18 SECONDS

The second example is of data taken about 9:30 AM local time between 16.0 and 16.9 MHz. The region swept was right at the MUF. The amplitude plot in the upper record of Figure 11 shows severe amplitude fluctuations increasingly close together as frequency increases and then tailing off as the MUF is passed. The dispersion results in a 1600 degree peak to peak phase error. The transformed signal shown in the lower record of Figure 11 is spread out over about 35 μ sec. Corrected transforms one and two seconds later are considerably better as seen in Figure 12. Further corrections 10 to 12 seconds after the first sweep show sidelobes rising, mostly on the lefthand side. This unbalanced result is typical of a multi-path situation. The missing sweeps in both examples are due to equipment difficulties.

The last example is for a pair of 3.0 MHz sweeps between 15.0 and 18.0 MHz taken at 7:45 PM local time. The sweeps were 5.0 seconds apart. In general, the effort to obtain 3 MHz data was hindered by the limited data sampling rate imposed by the maximum stepping rate of the digital stepping recorder being used. The receiver was limited to a bandwidth of 50 Hz which was, in turn, equivalent to a 50 μ sec range gate due to the time-frequency mapping of the linear FM. In this case, however, the receiver output stayed within the 50 Hz passband over the 3 MHz sweep region. Amplitude and phase between 15 and 18 MHz are shown in Figure 13. ϕ_1 , peak to peak, is 5345 degrees. The central sections of the uncorrected and corrected transforms are shown in Figure 14. The 300 nanosecond resolution, inherent in the

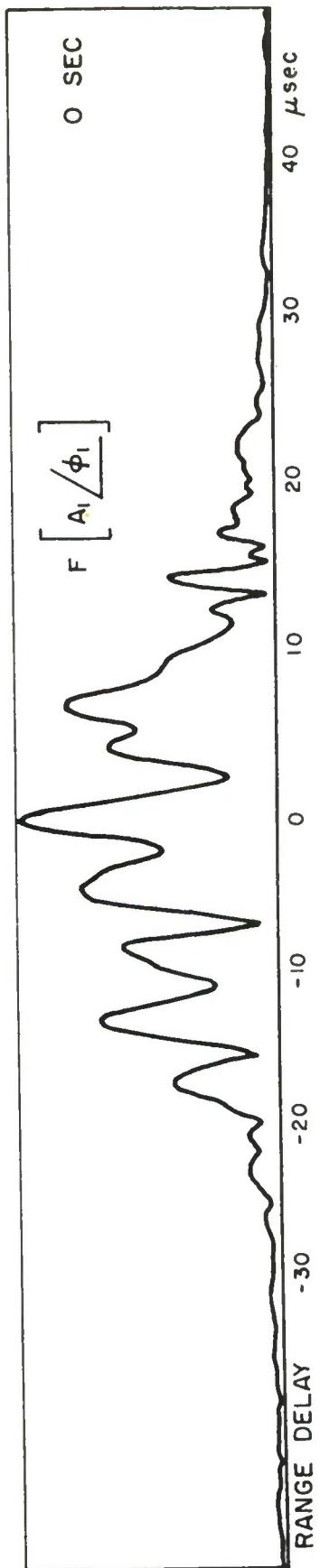
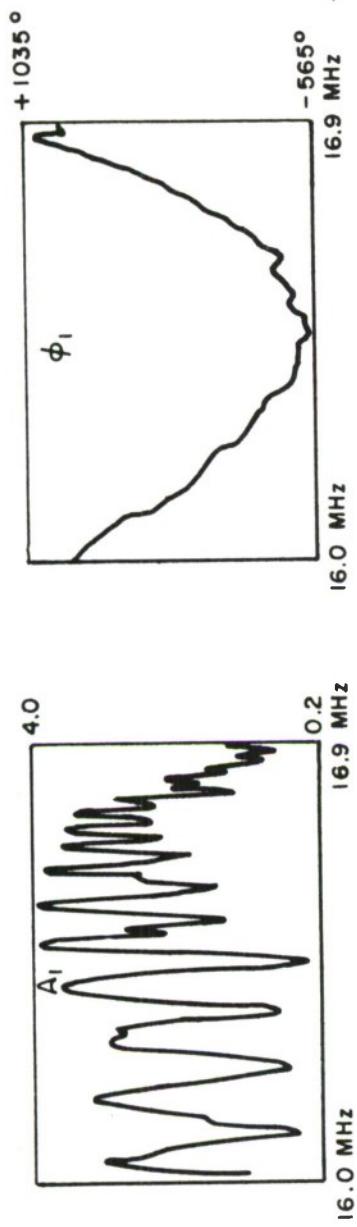


Figure II
 UPPER TRACE : AMPLITUDE (A_i) AND PHASE (ϕ_i) VERSUS FREQUENCY OVER 900 KHz BAND AT THE MUF
 LOWER TRACE : TRANSFORM OF UPPER TRACE

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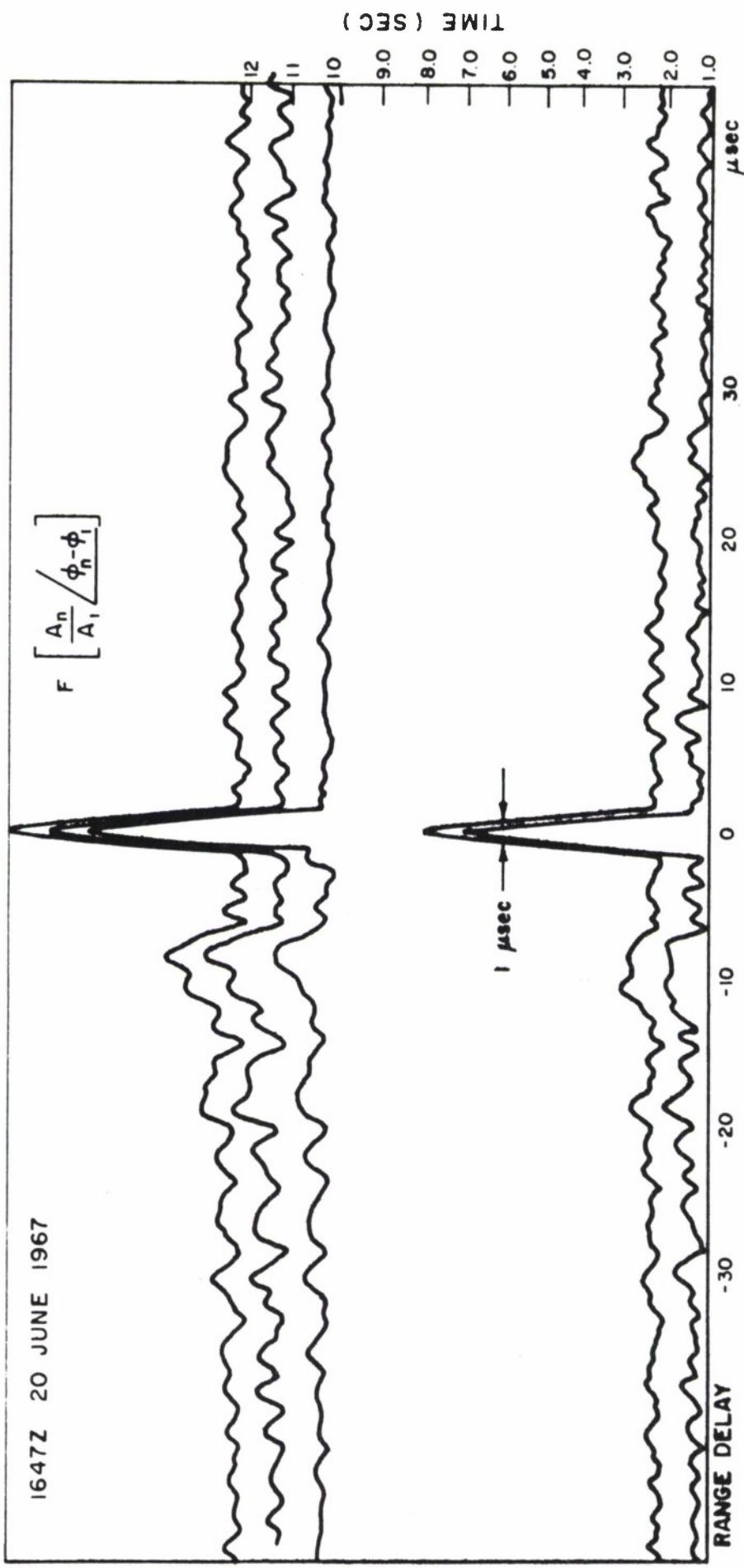


Figure 12 CORRECTED TRANSFORMS UP TO 12 SECONDS LATER

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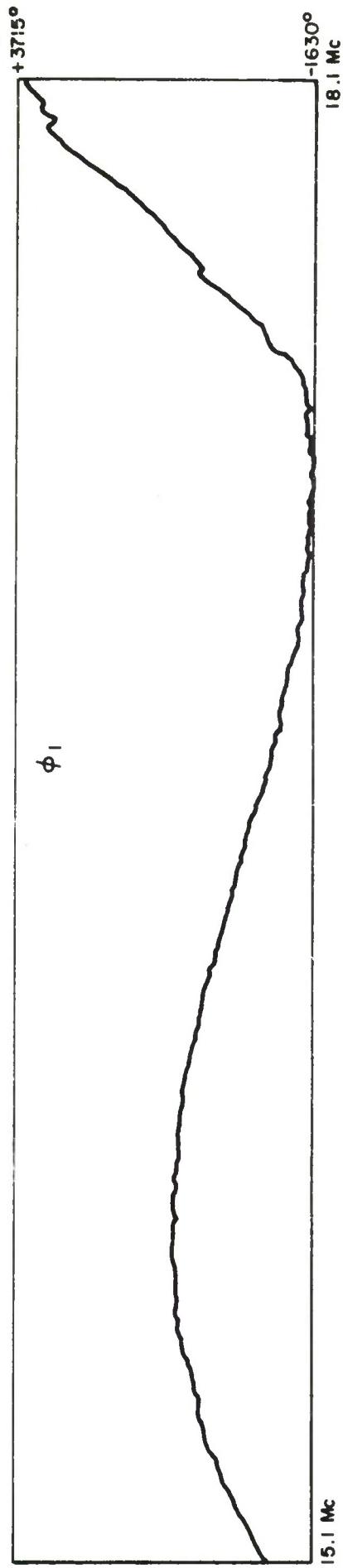
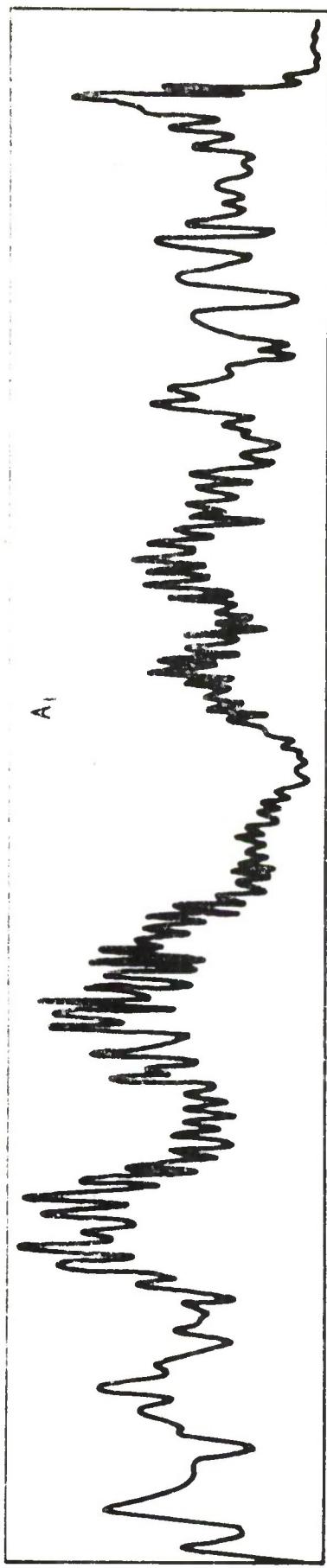


Figure 3 AMPLITUDE (A) AND PHASE (ϕ) VERSUS FREQUENCY OVER A 3 MHz BAND

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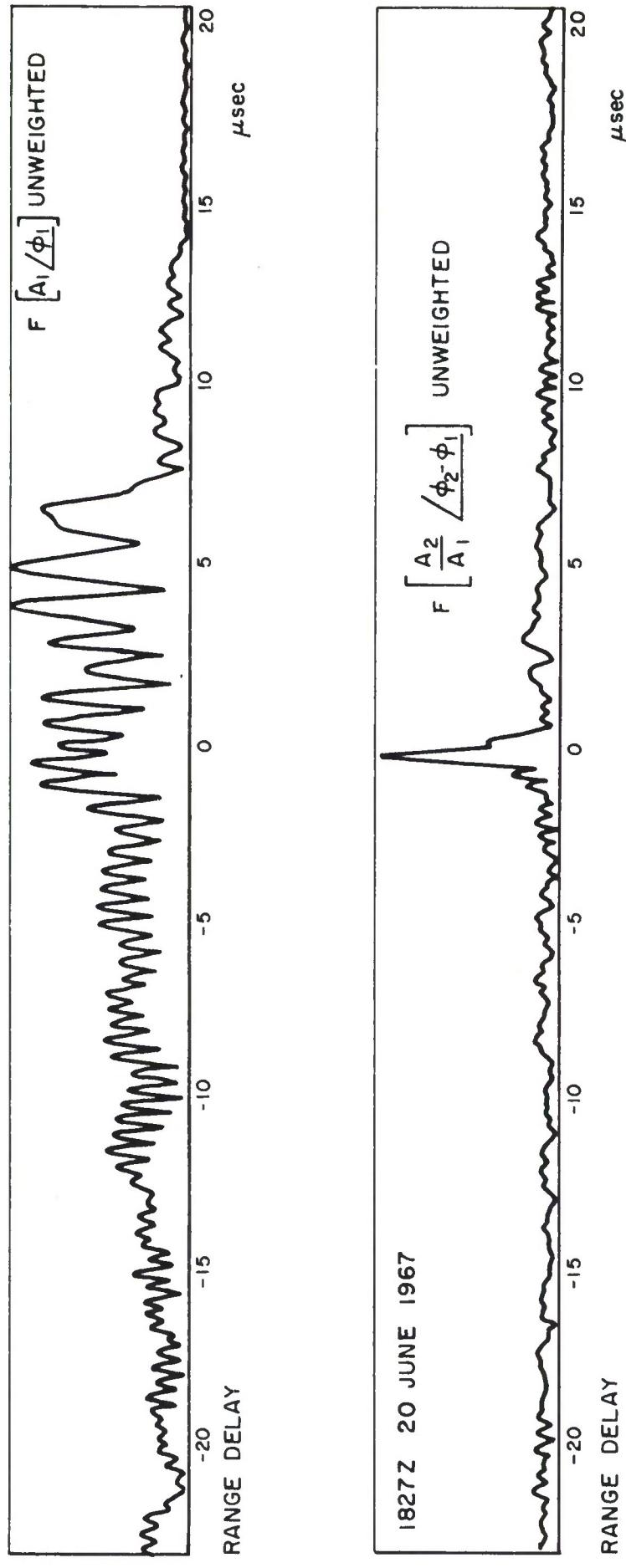


Figure 14. DISTORTION CORRECTION OVER A 3 MHz BAND
UPPER RECORD: UNCORRECTED FOURIER TRANSFORM
LOWER RECORD: CORRECTED FOURIER TRANSFORM 5 SECONDS LATER

waveform, is achieved five seconds after the original sweep. These transforms were not weighted, thus the sidelobes shown on the corrected transform are surprisingly good.

In addition to the processing described above, which basically consists of computing Equation (4) for each case, two other analysis techniques were employed. Instead of comparing the first sweep with all subsequent sweeps of a group, each sweep was compared with the next one. Thus, the following weighted transform was computed:

$$\mathcal{F} \left[\left(\frac{A_n}{A_{n-1}} \right)_{\text{wtd}} \angle \phi_n - \phi_{n-1} \right] \quad (5)$$

This analysis technique simulates the case where the ionospheric transfer function is measured and corrected for once every sweep. It was especially useful when analyzing a disturbed ionosphere. A result of this type is shown in Figure 15.

In another test, instead of a best straight line fit to the phase data a third order fit was computed. The Fourier transforms using the resulting residuals show that the delay dispersion is largely corrected for but higher order fluctuations caused by multipath phenomena are unaffected. One such result is shown in Figure 16.

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$$F \left[\frac{A_n}{A_{n-1}} \angle \phi_n - \phi_{n-1} \right]$$

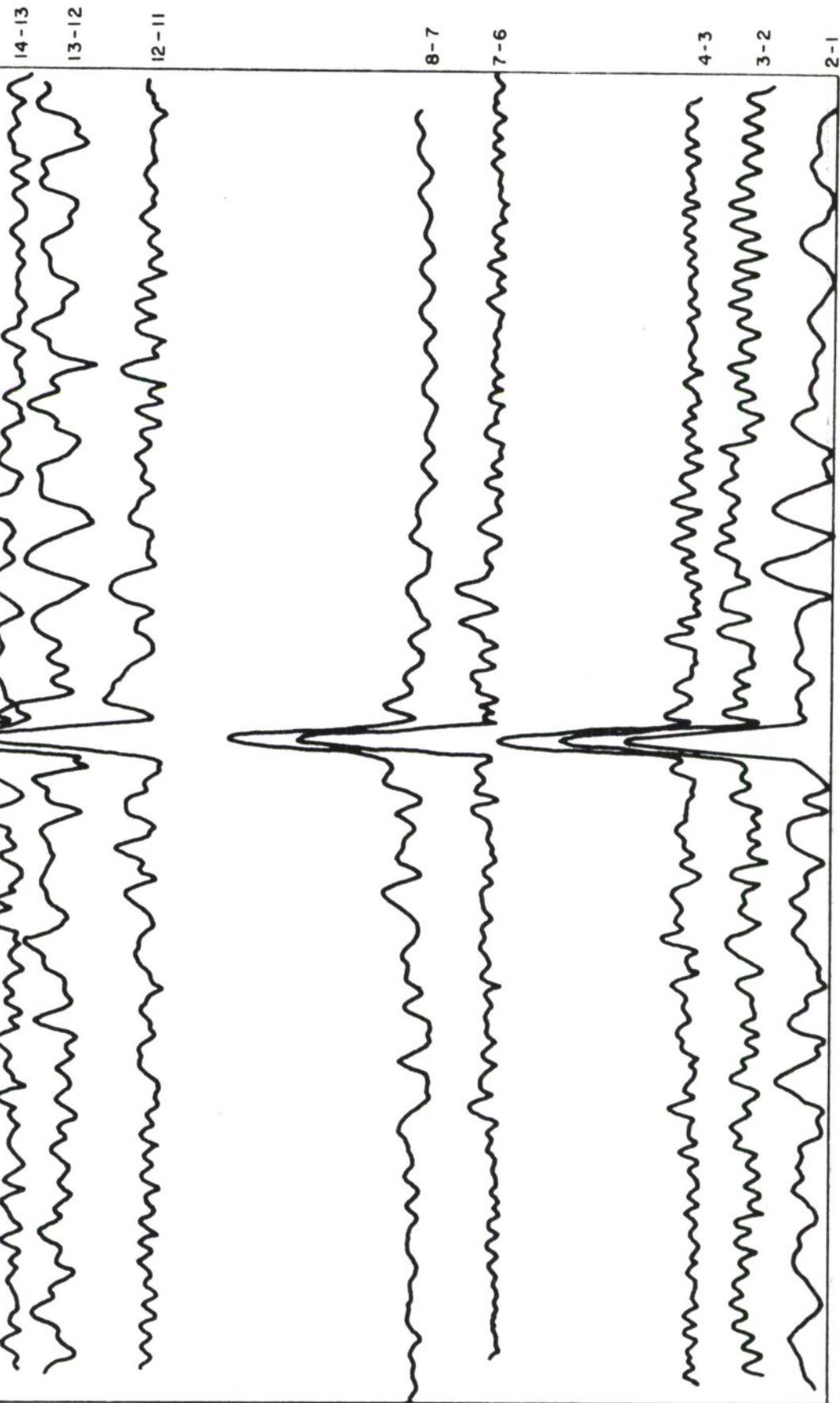
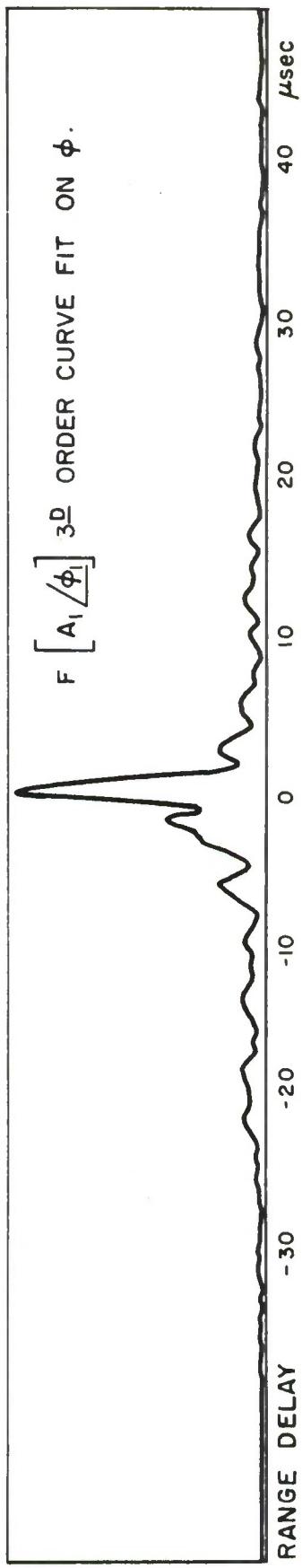
Figure 15 n^{th} SWEEP CORRECTED BY $(n-1)^{\text{th}}$ SWEEP

Figure 16 TRANSFORM OF A_1 AND THIRD ORDER CURVE FIT ON ϕ_1



SECTION VI

SUMMARY

An adaptive signal-processing technique capable of compensating for ionospheric distortion of broadband signals has been described. A computer study based upon data gathered in a joint MITRE-SEL experiment with the SEL coherent sounder has verified the practical feasibility of the processing technique. The transfer function of the ionosphere was measured over bandwidths of 350 kHz, 900 kHz and 3 MHz. These data displayed both dispersion and close multipath distortions. Application of the corrective processing technique to these data demonstrated that the dispersion can be corrected for periods up to eighteen seconds. The more rapidly varying distortions associated with the close multipath (which had rates up to one cycle per second) proved to be more difficult to compensate and were corrected for over correspondingly shorter times.

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

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Security Classification

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